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SPATIAL AND TEMPORAL TEMPERATURE STUDIES OF ELECTROTHERMAL CHEMICAL (ETC) PLASMAS

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MARCH 1992

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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13. ABSTRACT *(Maximum 200 words)*

Atomic spectroscopy has been used to measure plasma temperatures in the exit flow from a polyethylene capillary. Typical events involve the deposition of about 300 J of energy. Temperature values observed range from 10,000 K to almost 50,000 K, the latter the result of shock wave heating of the supersonic exit flow. Under the most favorable signal to noise conditions, uncertainties are estimated at 5%.

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1. INTRODUCTION

The temperature in the capillary and during the interaction of the plasma with the working fluid is a major unknown parameter required for the detailed modeling and design of electrothermal chemical (ETC) guns or accelerators. In the present study, we have continued our use of a bench-top plasma to develop a temperature diagnostic based on atomic spectroscopy that will be applied to full-scale systems. We have also observed temperature variations in the flow field that develops as the plasma exits from the plasma capillary orifice.

2. EXPERIMENTAL

The experimental configuration was similar to that previously reported[1]. A 675-J power supply with a pulse-forming network for tailoring the current pulse shape transfers energy into a plasma fixture consisting of a polyethylene capillary, steel holder, and aluminum wire for initiation of the event. The basic configuration of the capillary and its holder is shown in Figure 1. For most of the experiments described here, the capillary was a 4.5-mm-dia, 32-mm-long hole bored into a polyethylene rectangular bar 75 mm long and 10 mm square. The holder is made of two halves of a 75-mm-dia gun-steel cylinder held together by a high-strength c-clamp. The exit orifice is about 6 mm in diameter. The plasma is started by vaporizing a 0.11-mm- (0.004-in) dia aluminum wire. The design as shown is superior for these studies to that used previously[1] in two respects. The first advantage is that optical access is possible very near the capillary exit. The second improvement, replacing the ten bolts of the earlier fixture with a c-clamp, allowed for more data to be acquired in reasonable time. For emission studies, light was gathered with a single 0.2-mm-dia fused silica optical fiber held in a 1.0-mm-dia stainless steel tube to protect it from the force of the plasma. Light detection was as before with an Optical Multichannel Analyzer (OMA) (PARC model 1420) mounted on either 0.25-m and 0.33-m focal length spectrographs, with 1,200 and 2,400 line/mm gratings, respectively. These two combinations allowed either sufficiently broad spectral coverage to see four strong barium lines or provided higher resolution to see one pair of the barium transitions in detail to ascertain that they were clean atomic transitions and to

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[1] Bunte, S. W., and R. A. Beyer. "Temperature Measurements of ET Plasmas." Proceedings of the 26th JANNAF Combustion Meeting, CPIA Publication No. 529, vol. III, p. 91, 1989.

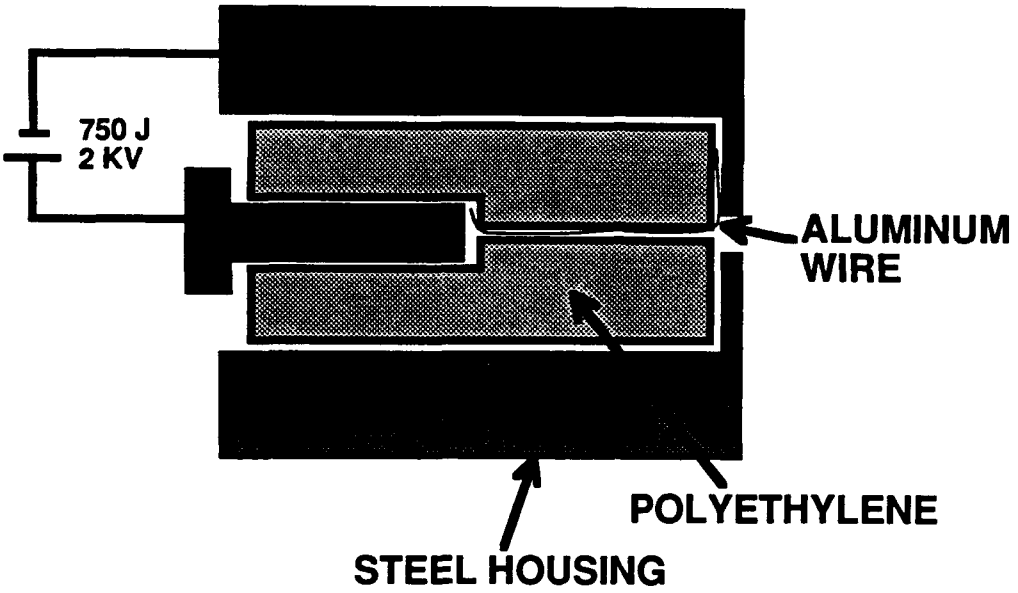


Figure 1. Schematic Drawing of Polyethylene Capillary and Electrodes.

provide information on the emission line width. For all of the observations reported here, the detector was gated on at varying times during the plasma event. For the absorption studies, a 4-μs duration xenon flash lamp was triggered in synchronization with the OMA detector.

The temperatures reported here are determined from the emission intensities by calculating for each line the value of {intensity•wavelength/g•A} where g is the degeneracy of the lower level and A is the Einstein A coefficient of the transition.[2] The intensities used are peak heights. This approach was judged to be more reliable because of noise in the data. The assumption is implicit that line shapes are constant across the energy range. The parameter in brackets is proportional to the number density in a state and is here referred to as the "number density." If one assumes local thermodynamic equilibrium, then the temperature is determined from the (straight line) slope of a semilogarithmic plot of the number density vs. the energy of the upper state. For the cases where four transitions are recorded, a curve fitting program is used to determine this slope. For much of the higher

[2] Griem, H. R. Plasma Spectroscopy. New York: McGraw-Hill, p. 270, 1964.

resolution data discussed here, the line is determined by two points and the uncertainty is probably greater but harder to define.

A typical set of curves describing the electrical characteristics of the plasma discharge is shown in Figure 2. The values measured are the current (kA) and voltage (kV) across the capillary; the power (kW) and energy (kJ) are calculated from them. Also shown in this figure is a typical OMA gate pulse (the one shown corresponds to data discussed later in this report). In this example, the total energy deposited in the discharge is about 285 J, or 42% of that stored in the power supply. Mass loss by the components was measured for some of the discharges. One set of carefully measured values with the earlier capillary holder[1] was 1.6 mg for the polyethylene, 12.0 mg for the stainless steel anode, and 9.8 mg for the graphite nozzle. It is not known at present how typical these values are or how wide the variation in them might be. In the new design, the integral nozzle/capillary holder have a total mass too great to determine the mass loss per shot in our laboratory. The mass loss of the anode appears to be variable, and may be the source of some of the plasma variations discussed later.

3. ABSORPTION MEASUREMENTS

Absorption measurements were tried under a variety of conditions in order to avoid the effects of self-absorption as reported earlier in emission studies, and to make a determination of the optical density of our plasmas. Little was done to make detailed quantitative temperature measurements with absorption. However, the ratios of the barium lines observed were similar in absorption and emission. A typical absorption spectrum is shown in the upper trace of Figure 3. Also shown on this plot is the emission record from a barium cold cathode lamp for comparison (lower trace). Prominent barium lines are indicated near 4,525, 4,554, and 4,934 Å. As can be seen, the plasma is fairly well behaved and not overly dense for making measurements.

The difference between absorption and emission was marked for some atoms and molecular transitions observed. An example is the case of the atomic aluminum transitions near 3,944 Å and 3,962 Å. These lines were very weak in emission but had intensity comparable to the strongest barium lines in absorption. Similarly, for many of the strong

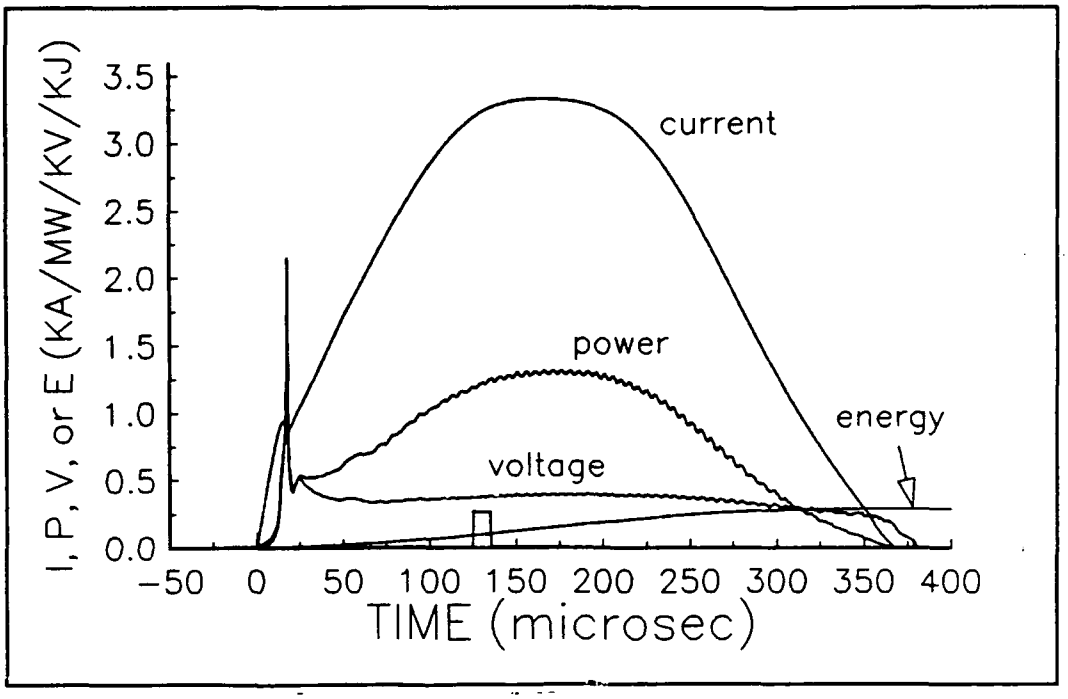


Figure 2. Electrical Characteristics of Typical Event With 4.5-mm Diameter Polyethylene Capillary.

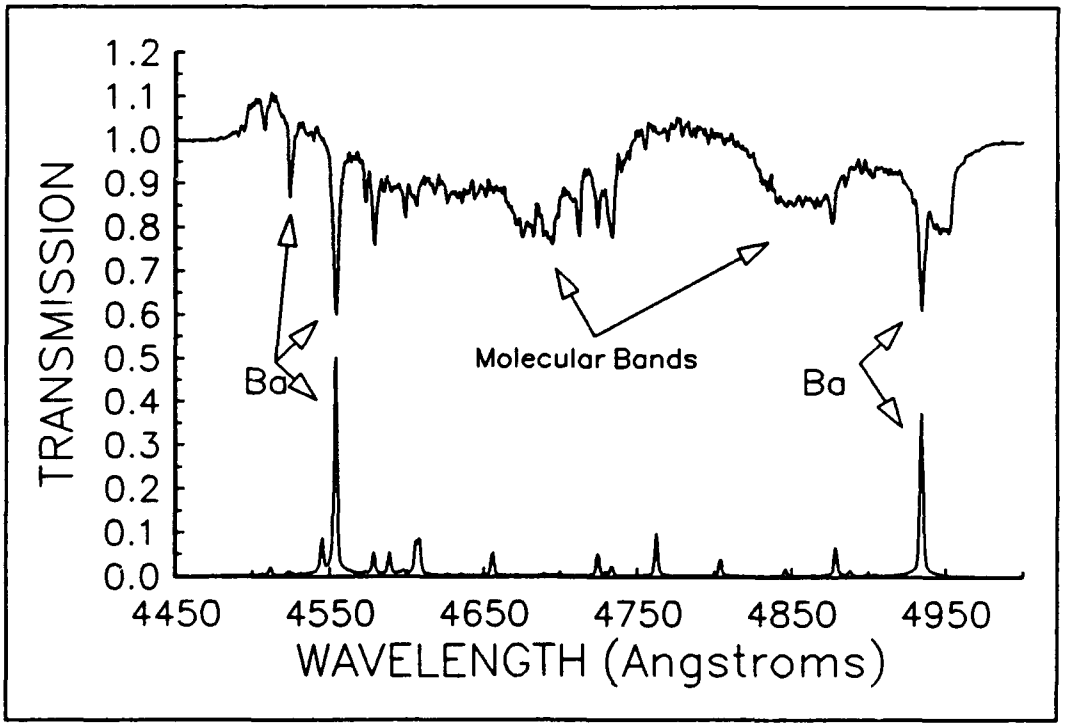


Figure 3. Pulsed Absorption in Plasma (Upper Curve) With Strong Barium Peaks Indicated and Reference Spectrum (Lower Curve) From Cold Cathode Lamp.

molecular transitions observed, such as those shown in Figure 3, there was not always a strong correlation between absorption and emission spectra. No attempt was made to identify the majority of the molecular transitions observed.

An example of an identifiable molecular transition is shown in Figure 4, where an absorption trace (upper curve) is compared to the well-known C_2 Swan band emission from a methane/nitrous oxide flame (lower curve). The band heads are near 5,165 Å and 5,129 Å. Also quite obvious in this figure is the presence of an equally strong absorption band head near 5,210 Å, which was not identified. Molecular transitions identified in other spectra included several bands of OH near 3,100 Å and BaOH near 4,870 Å. Other transitions that might be both expected and easily recognizable, such as those of CH, were not seen. The temperatures here, although often not as hot as expected at the outset of these measurements, were still well above typical flame temperatures, making relative band populations and band shapes appear unfamiliar. Some brief attempts to find a suitable molecular thermometer among a higher lying system were unsuccessful. These numerous molecular bands were not anticipated and were a major source of noise in our atomic spectroscopy studies. Although they were common features of the observed spectra, the molecular transitions was frequently inconsistent in intensity. At the higher temperatures discussed later, they were far below the atomic emission intensities. This effect may be due either to the distribution of intensity over many states or from thermal dissociation of the molecules.

4. BARIUM EMISSION STUDIES

Once it had been established that the optical density was not a problem in these studies, it was decided to pursue a systematic set of observations using singly ionized barium (Ba II) emission as the thermometer. Two important reasons for this choice were that the "line of sight" characteristic of absorption can possibly be diminished or eliminated in emission studies, and that fiber optic probes into the flow are more readily devised for emission studies. The self-absorption that was seen in some of our earlier studies was not a problem under the conditions applied here. Temperatures were calculated from the spectra using the ratios of intensities of emission from atomic states separated by about 2.5 eV, as shown in Figure 5. Under low resolution, four main lines were used—those at 4,525, 4,554, 4,900, and 4,934 Å.

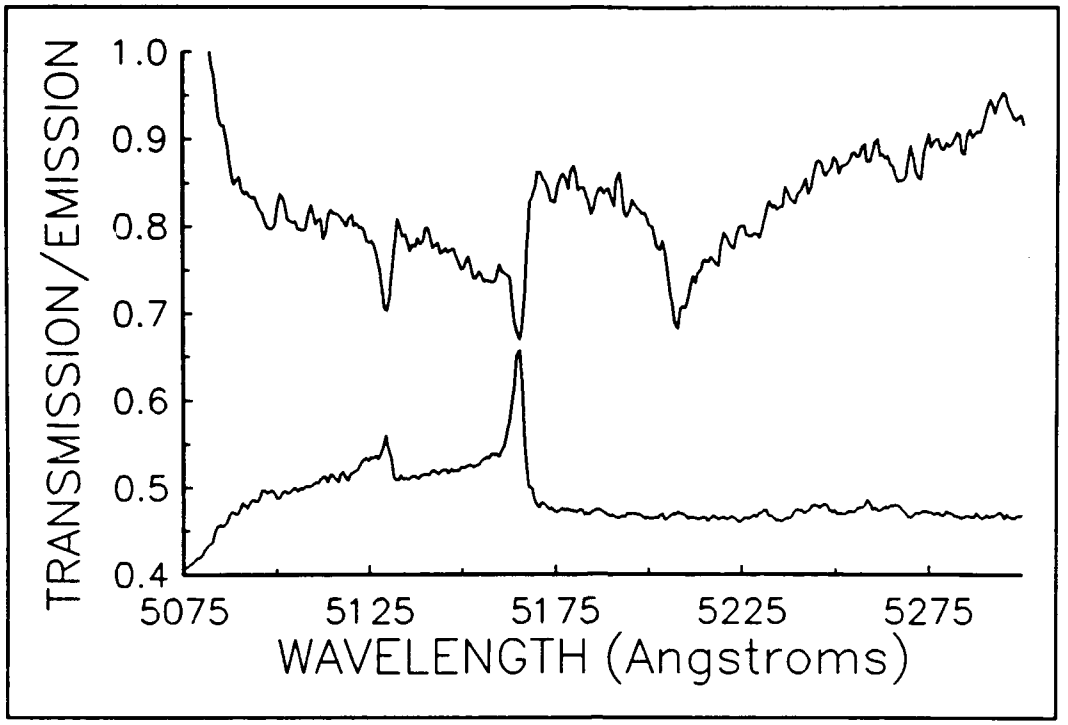


Figure 4. Pulsed Absorption in Plasma (Upper Curve) and C_2 Swan Band Emission From CH_4/N_2O Flame (Lower Curve).

A typical straight-line fit to the data from an intermediate temperature example is also shown in Figure 5. The results of the plot shown are 21,000 K, with a standard deviation of about 1,000 K. Statistical uncertainties vary widely from shot to shot, but are typically about 5%. Total error is more difficult to quantify and is the subject of on-going efforts.

In order to explore the spatial variation of the temperature as the plasma exits the orifice and expands into the ambient air, the fiber optic probe was moved systematically to a series of positions at various distances from the orifice. The detector was gated at the same time (130 μs after start of current flow) for the entire series, as shown in Figure 2. Thus, if the events are reproducible, the result is a snapshot of the temperature profile at this time. For this series, spectra were recorded with the higher resolution spectrograph in an attempt to correlate spectral line width with temperature as determined from intensity. Thus, the uncertainties are not well quantified; however, as will be seen, the trend in temperatures is obvious.

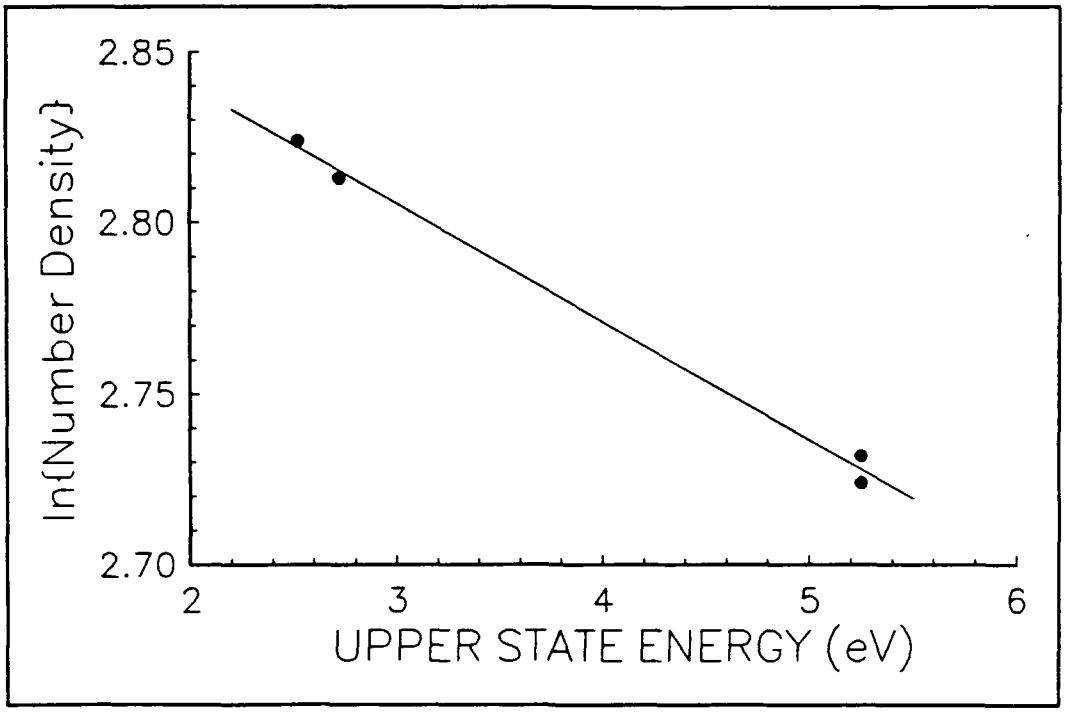
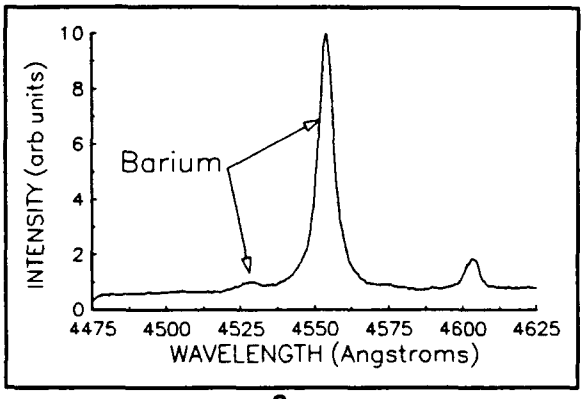
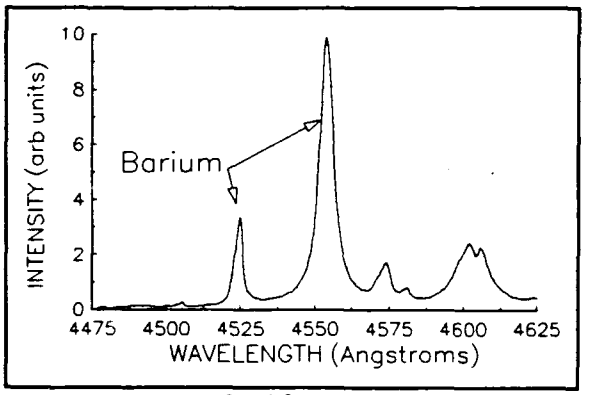


Figure 5. Natural log of Number Density Plotted vs. Upper State Energy and the Linear fit to the Points for Temperature Determination.

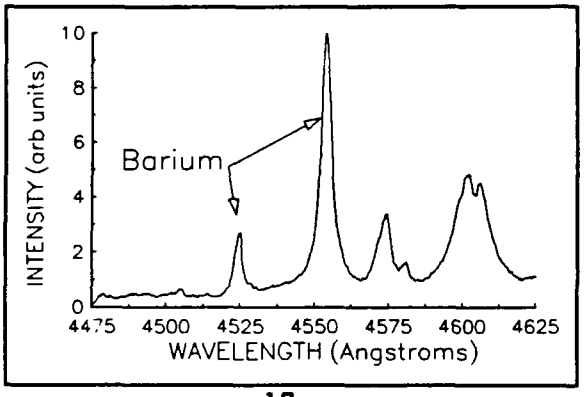
The spectra recorded at distances from 2 to 45 mm are shown in Figure 6. Two obvious indications of changing plasma conditions are present—the relative peak heights of the barium lines (4,525 Å and 4,554 Å) and the half width of the 4,554 Å line. The 4,525 Å line is emission from a barium ion (Ba II) state with 5.25 eV of energy; the 4,554 Å line is from a state of the same ion with 2.72 eV of energy. Thus, the relative peak intensities are indicative of changing relative populations in these states, which we relate to temperature changes, as previously discussed. Attempts to do a sophisticated curve fit to the emission lines to determine Lorentzian and Gaussian components and perhaps infer Stark (plasma) vs. Doppler (thermal) broadening was inconclusive. No attempt has been made to identify or analyze the other peaks shown in Figure 6. The temperatures calculated from the peak heights are shown in Figure 7 as a function of distance. The symbols in this figure are not error limits, but were chosen to suggest approximately the uncertainty in the temperature measurements. The sharp temperature rise indicated in this figure was reproducible on many days, but it was not always present. The parameter that is changing has not yet been identified. Possibilities will be discussed in Section 5.



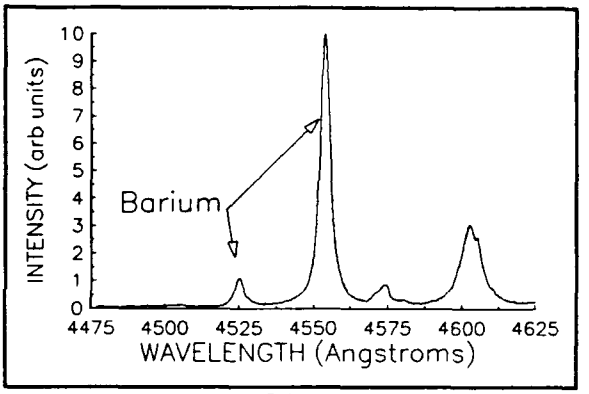
a. 2 mm



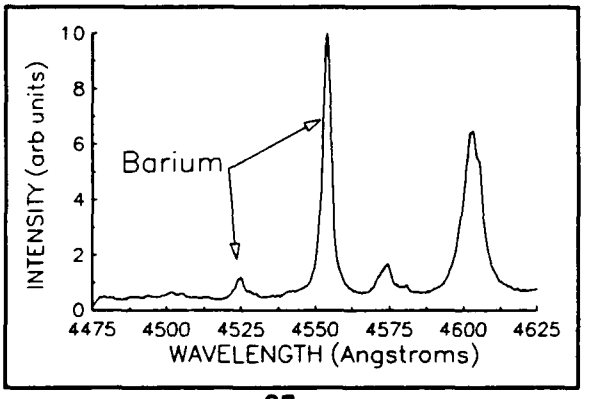
b. 10 mm



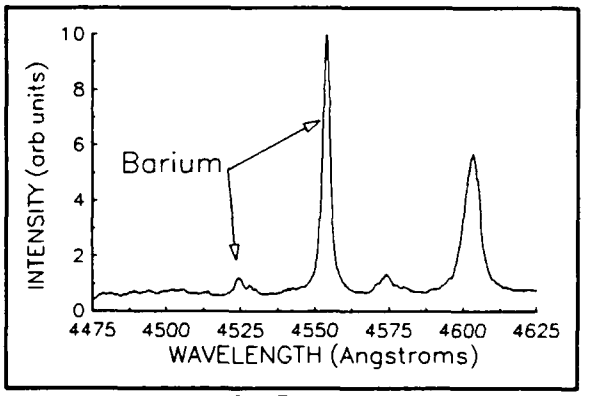
c. 15 mm



d. 25 mm



e. 35 mm



f. 45 mm

Figure 6. Barium Emission Spectra at 4,525 Å and 4,554 Å Showing Variation of Relative Intensities With Distance From Exit Orifice.

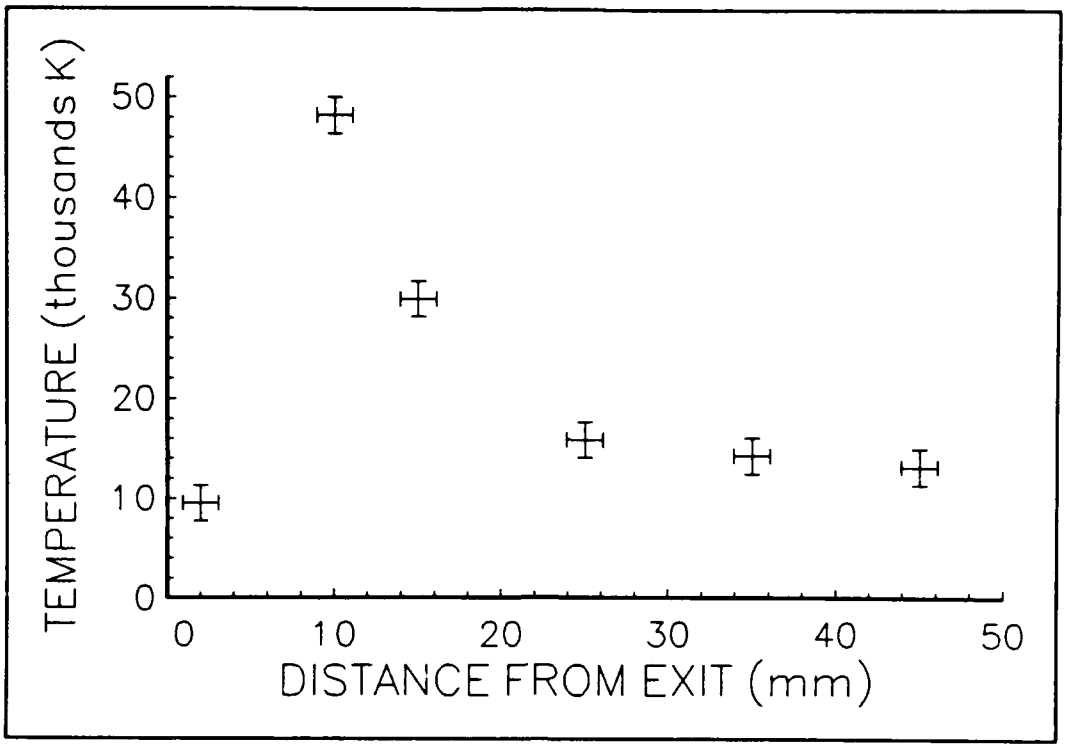


Figure 7. Temperatures Calculated From Barium Emission Spectra of Figure 6 as Function of Distance From Exit Orifice.

5. DISCUSSION

The most prominent feature of the data presented in this report is the obvious, and probably not surprising, shock wave formation as the plasma exists the capillary. Of particular note is the high temperatures which approach 50,000 K compared to the 10,000 K temperatures in the region at the orifice. From gun muzzle flow field experience, the phenomenolgy of the formation of this shock and corresponding temperature pattern are not surprising. Without detailed knowledge of the equation of state of these plasmas, a calculation of the temperatures from a shock formation like this is not possible. This phenomenon clearly needs to be explored in more detail, since in the ETC gun environment the plasma is expanding into an even higher pressure region.

Of great concern to the experimentalist is the lack of consistent reproducibility of the shock behavior. It would be consistently reproducible for several consecutive days and then disappear for a day or two. Although plasma current and voltage were not monitored

precisely, there were no indications of significant changes in the energy deposited into the capillary under these two greatly differing circumstances (with and without shock wave formation). In future work, the electrical characteristics will be monitored much more closely. Other possibilities to be explored include the following. First, the discharge may attach itself on the front of the steel capillary holder in varying fashions, which would affect the impedance of the circuit. Second, the interior surface of the capillary may be affected by atmospheric conditions, such as relative humidity. Third, the wire may vaporize in slightly different fashion due to length, bending, handling, surface impurities, or the manner of electrical contact. Fourth, the sound speed of the plasma may be varying significantly because of changed composition, perhaps from the variation in the amount of heavy atoms deposited into the plasma from the electrodes.

Aside from the shock variations, the measurements do show consistency and reproducibility of the temperatures under these conditions.

6. FUTURE STUDIES

The first additional efforts will be directed toward studying the shock behavior more thoroughly as a function of time and position. Other studies anticipated include adding an exit nozzle to the polyethylene capillary to change discharge flow rates, measuring the internal temperature with a fiber optic probe, studying the temperature during plasma interaction with simple working fluids such as water, and varying capillary geometry and total energy input to more nearly simulate gun conditions (i.e., to increase plasma current density at least one order of magnitude).

7. CONCLUSION

Measurements have been made as a function of time and position in a pulsed plasma. Typical plasma exit temperatures from the polyethylene capillary range from 10,000 K to 15,000 K. The supersonic flow of the plasma from the orifice produces a shock disk which raises the temperature outside this device to apparent temperatures almost five times as great as at the capillary exit. Further studies and modeling of this behavior are required to define the implications, if any, to ETC gun devices.

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